

# The $ZZ'$ kinetic mixing in the light of the recent direct and indirect dark matter searches

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Several constructions, of stringy origins or not, generate abelian gauge extensions of the Standard Model (SM). Even if the particles of the SM are not charged under this extra  $U'(1)$ , one cannot avoid the presence of a kinetic mixing between  $U'(1)$  and the hypercharge  $U_Y(1)$ . In this work, we constraint drastically this kinetic mixing, taking into account the recent experimental data from accelerator physics, direct detection and indirect detection of dark matter. We show that the region respecting WMAP and experimental constraints is now very narrowed along the pole line where  $M_{Z_D} \simeq 2m_{DM}$ ,  $Z_D$  being the gauge boson associated to the extra  $U'(1)$ .

## I. INTRODUCTION

Neutral gauge sectors with an additional dark  $U_D(1)$  symmetry in addition to the Standard Model (SM) hypercharge  $U(1)_Y$  and an associated  $Z_D$  ("D" standing for *Dark*) are among the best motivated extensions of the SM, and give the possibility that a dark matter candidate lies within this new gauge sector of the theory. Extra gauge symmetries are predicted in most Grand Unified Theories (GUTs) and appear systematically in string constructions. Larger groups than  $SU(5)$  or  $SO(10)$ , like  $E_6$  allows the SM gauge group to be embedded into them. Brane-world  $U'(1)$ s are special compared to GUT  $U'(1)$ s because there is no reason for the SM particle to be charged under them: for a review of the phenomenology of the extra  $U'(1)$ s generated in such scenarios see e.g. [1]. In such framework, the extra-gauge boson would act as a portal between the *dark* world (particles not charged under the SM gauge group) and the *visible* sector through its gauge invariant kinetic mixing  $\delta/2 F_Y^{\mu\nu} F_{\mu\nu}^D$  [2–10]. One of the first model of dark matter from the hidden sector with a massive additional  $U'(1)$  through both mass and kinetic mixings, the so called dark force can be found in [11]. The Dark Matter (DM) candidate  $\psi_0$  would be the lightest (and thus stable) particle of this secluded sector. Such a mixing has been justified in recent string constructions [13–16], but has also been studied with a model independent approach [3, 12, 17, 18].

On the other hand, recently the CRESST-II and CoGENT collaborations have reported the observation of low-energy events in excess of known backgrounds [19, 20]. This has encouraged the hypothesis that these signals -in addition to the long-standing DAMA [21] annual modulation signal – might arise from the scattering of a light ( $\sim 10$  GeV) dark matter particle. It was recently shown that models with extra  $U'(1)$  can easily accommodate with such signals [22–25]. Similar models with singlet extension reached the same conclusion because they are very similar in the construction than the

models with extra gauge boson, except that the role of the portal is played by the Higgs boson [26, 27]. Other *very* important astrophysical consequences from the tri-bosonic coupling  $Z_D YY$  generated by loop induced triangle diagrams are studied in [28–30] and in [31] in a more model independent way. Consequences of such anomaly-generated vertex are also well analyzed in [32, 33]. It is worth noticing that one can easily build a model where the  $Z_D$  becomes the DM candidate [34]: a clear summary of all these extensions can be found in [35].

Our objective in this work is to restrict the parameter space of an extra  $U_D(1)$ , taking into consideration the main detection modes, *i.e.* cosmological data, precision measurements, direct and indirect detection searches of dark matter. The paper is organized as followed: after a brief reminder of the model and its phenomenological characteristics, we analyze the experimental exclusion limits (in a conservative way) in different regimes ((very)light and (very)heavy DM), before presenting a general analysis and perspective for a XENON-like 1 ton detector. We then conclude.

## II. THE MODEL

The matter content of any *dark*  $U(1)_D$  extension of the SM can be decomposed into three families of particles:

- The *Visible sector* is made of particles which are charged under the SM gauge group  $SU(3) \times SU(2) \times U_Y(1)$  but not charged under  $U_D(1)$  (hence the *dark* denomination for this gauge group)
- the *Dark sector* is composed by the particles charged under  $U_D(1)$  but neutral with respect of the SM gauge symmetries. The dark matter ( $\psi_0$ ) candidate is the lightest particle of the *dark sector*
- The *Hybrid sector* contains states with SM and  $U_D(1)$  quantum numbers. These states are fundamental because they act as a portal between the two previous sector through the kinetic mixing they induce at loop order.

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From these considerations, it is easy to build the effective Lagrangian generated at one loop :

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SM}} - \frac{1}{4} \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{\delta}{2} \tilde{B}_{\mu\nu} \tilde{X}^{\mu\nu} \\ & + i \sum_i \bar{\psi}_i \gamma^\mu D_\mu \psi_i + i \sum_j \bar{\Psi}_j \gamma^\mu D_\mu \Psi_j \end{aligned} \quad (1)$$

$\tilde{B}_\mu$  being the gauge field for the hypercharge,  $\tilde{X}_\mu$  the gauge field of  $U_D(1)$  and  $\psi_i$  the particles from the hidden sector,  $\Psi_j$  the particles from the hybrid sector,  $D_\mu = \partial_\mu - i(q_Y \tilde{g}_Y \tilde{B}_\mu + q_D \tilde{g}_D \tilde{X}_\mu + g T^a W_\mu^a)$ ,  $T^a$  being the  $SU(2)$  generators, and

$$\delta = \frac{\tilde{g}_Y \tilde{g}_D}{16\pi^2} \sum_j q_Y^j q_D^j \log \left( \frac{m_j^2}{M_j^2} \right) \quad (2)$$

with  $m_j$  and  $M_j$  being hybrid mass states [36].

Notice that the sum is on all the hybrid states, as they are the only ones which can contribute to the  $\tilde{B}_\mu \tilde{X}_\mu$  propagator. After diagonalization of the current eigenstates that makes the gauge kinetic terms of Eq.(1) diagonal and canonical, we can write after the  $SU(2)_L \times U(1)_Y$  breaking<sup>1</sup> :

$$\begin{aligned} A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \\ Z_\mu &= \cos \phi (\cos \theta_W W_\mu^3 - \sin \theta_W B_\mu) - \sin \phi X_\mu \\ (Z_D)_\mu &= \sin \phi (\cos \theta_W W_\mu^3 - \sin \theta_W B_\mu) + \cos \phi X_\mu \end{aligned} \quad (3)$$

with, at the first order in  $\delta$ :

$$\begin{aligned} \cos \phi &= \frac{\alpha}{\sqrt{\alpha^2 + 4\delta^2 \sin^2 \theta_W}} \quad \sin \phi = \frac{2\delta \sin \theta_W}{\sqrt{\alpha^2 + 4\delta^2 \sin^2 \theta_W}} \\ \alpha &= 1 - M_{Z_D}^2/M_Z^2 - \delta^2 \sin^2 \theta_W \\ &\pm \sqrt{(1 - M_{Z_D}^2/M_Z^2 - \delta^2 \sin^2 \theta_W)^2 + 4\delta^2 \sin^2 \theta_W} \end{aligned} \quad (4)$$

and  $+$  ( $-$ ) sign if  $M_{Z_D} < (>) M_Z$ . The kinetic mixing parameter  $\delta$  generates an effective coupling of SM states  $\psi_{\text{SM}}$  to  $Z_D$ , and a coupling of  $\psi_0$  to the SM  $Z$  boson which induces an interaction on nucleons. Developing the covariant derivative on SM and  $\psi_0$  fermions state, we

computed the effective  $\psi_{\text{SM}} \psi_{\text{SM}} Z_D$  and  $\psi_0 \psi_0 Z$  couplings at first order<sup>2</sup> in  $\delta$  and obtained

$$\mathcal{L} = q_D \tilde{g}_D (\cos \phi Z'_\mu \bar{\psi}_0 \gamma^\mu \psi_0 + \sin \phi Z_\mu \bar{\psi}_0 \gamma^\mu \psi_0). \quad (5)$$

We took  $q_D \tilde{g}_D = 3$  through our analysis, keeping in mind that our results stay completely general by a simple rescaling of the kinetic mixing<sup>3</sup>  $\delta$ .

### III. CONSTRAINTS

We drove a complete analysis of the allowed parameter space for the kinetic mixing using the more recent searches in accelerator physics, direct and indirect detection experiments. Here follows a summary of the constraints we applied in our study:

#### A. Low energy and electroweak constraints

Concerning the electroweak symmetry breaking, the mixing between  $\tilde{X}_\mu$  and  $\tilde{B}_\mu$  generates new contributions to precision electroweak observables. However, none of the particle of the SM has any  $U_D(1)$  charges: the  $U_D(1)$  can be considered has a *lepto-hadrophobic*  $Z_D$ . Other authors in [3] or [16] have looked at hidden-valley like models or milli-charged dark matter but concentrating their study to relatively heavy  $Z_D$  and a large mixing angle. We summarize in this section the main constraints generated by such data.

#### • g-2 :

The presence of a light  $Z_D$  can contribute to the anomalous magnetic moment of the muon,  $a_\mu = (g_\mu - 2)/2$ . For our analysis we implemented the formulation of Ref.[37]. To compare with experimental data, we used the latest experimental value [38]

$$\delta a_\mu = (31.6 \pm 7.9) \times 10^{-10} \quad (6)$$

We also checked that parity-violation effects [37] constrain a much smaller region of the parameter space.

<sup>1</sup> Our notation for the gauge fields are  $(\tilde{B}^\mu, \tilde{X}^\mu)$  before the diagonalization,  $(B^\mu, X^\mu)$  after diagonalization and  $(Z^\mu, Z_D^\mu)$  after the electroweak breaking.

<sup>2</sup> One can find a detailed analysis of the spectrum and couplings of the model in the appendix of [17].

<sup>3</sup> The author would like to thank the referee for having pointed out this detail of the analysis.

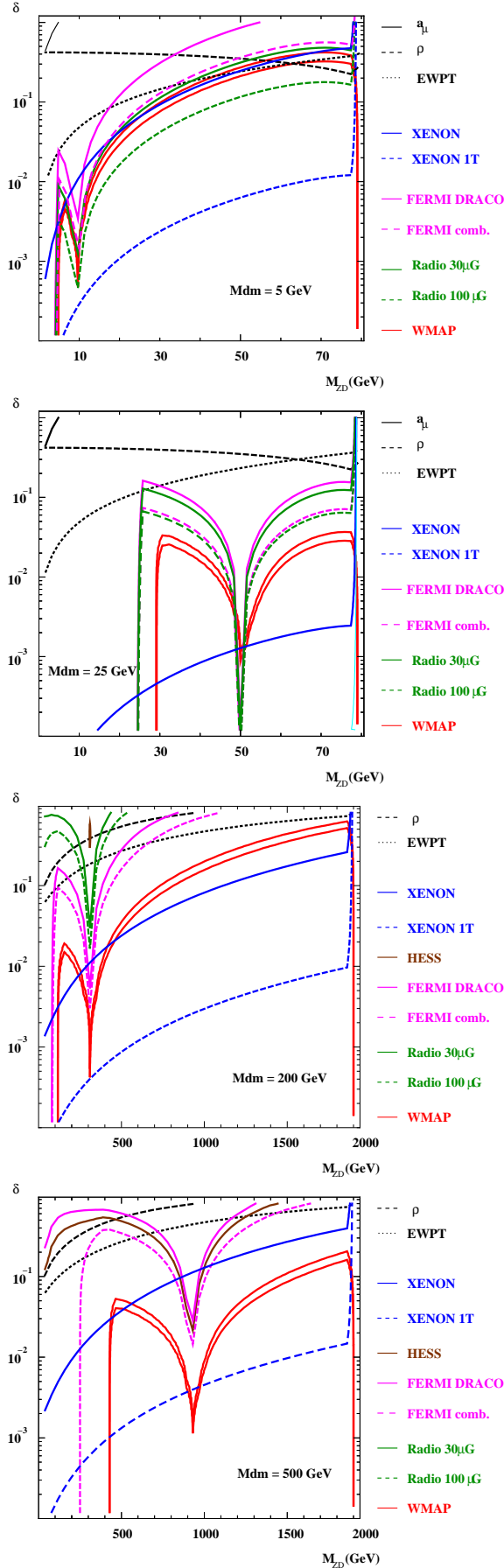


FIG. 1. Precision test, relic density, direct detection and indirect detection constraints in the plane  $(M_{Z_D}; \delta)$  for different masses of Dark Matter (5, 25, 200 and 500 GeV)

- $\rho$  parameter :

The  $\rho$  parameter is defined as  $\rho = m_W^2/m_Z^2 c_W^2 = 1$  in the Standard Model (SM). Any electroweak extension of the SM can generate a deviation to the  $\rho$  parameter, especially if  $M_{Z_D} \simeq M_Z$ , where the mixing is maximum. One can thus translate the global fit of the  $\rho$  parameter  $\rho - 1 = 4_{-4}^{+8} \times 10^{-4}$  [39] to a constraint on the  $(M_{Z_D}; \delta)$  plane.

- Electroweak precision test :

The authors of [32] have computed the observables from effective Peskin–Takeuchi parameters [40], and found

$$\begin{aligned} \Delta m_W &= (17 \text{ MeV}) \zeta \\ \Delta \Gamma_{l+l-} &= -(8 \text{ keV}) \zeta \\ \Delta \sin^2 \theta_W^{eff} &= -(0.00033) \zeta \end{aligned} \quad (7)$$

where

$$\zeta \equiv \left( \frac{\delta}{0.1} \right)^2 \left( \frac{250 \text{ GeV}}{M_{Z_D}} \right)^2 \quad (8)$$

More recently, the authors of [41] have published an extensive model independent analysis in the energy range of interest in our study. They bounded the kinetic mixing by  $\delta \lesssim 0.03$  for  $10 \text{ GeV} < M_{Z_D} < 200 \text{ GeV}$  which is in complete agreement with the constraints given by Eq.(7).

## B. Relic Density

The abundance of a thermal relic dark matter candidate  $\psi_0$  is controlled by its annihilation cross section into SM particles mediated by the exchange of a  $Z_D$  gauge boson through  $s$ -channel, or  $t$ -channel  $Z_D Z_D$  final state (see [28, 29] for a detailed study of the relic abundance constraints). We modified the micrOMEGAs2.2.CPC code<sup>4</sup> [42] in order to calculate the relic abundance of  $\psi_0$  and implemented the points that fulfill the WMAP  $5\sigma$  bound [43],  $\Omega_{DM} h^2 = 0.1123 \pm 5 \times 0.0035$ . One important point is that for a given  $M_{Z_D}$  and  $m_{\psi_0}$ , there exists a unique solution  $\delta$  (up to the very small uncertainties at  $5\sigma$ ) fulfilling WMAP constraints : from 3 parameters  $(m_{\psi_0}, M_{Z_D}, \delta)$ , the WMAP constraints reduce it to two  $(M_{Z_D}, \delta)$ .

<sup>4</sup> The author wants to thank particularly G. Belanger and S. Pukhov for their help to address this issue.

One want to stress that a zone with low relic abundance respecting WMAP is expected around the region where  $M_{Z_D} \simeq M_Z$ . This comes from the increase of the mixing angle  $\sin \phi$  in this region of parameter space. Indeed, for a given  $\delta$ ,  $\sin \phi$  increases by a factor of 10 when  $M_{Z_D}$  varies from 90 to 110 GeV (Eq.(4)), decreasing the relic abundance by a factor 100 (the  $Z_D \bar{f} f$  coupling is proportional to  $\sin \phi$ ).

### C. Direct detection

There was recently a huge interest concerning the exclusion (or not) of the CoGENT/DAMA/CRESST signal region corresponding to light dark matter [19–21, 44]. Several authors tried to re-conciliate the signal with minimal-like extensions of the standard model : scalar dark matter, extra U(1), .. Very recently, XENON experiment released a likelihood approach to the first results from XENON100 [45]. We took their  $2\sigma$  limits on their spin-independent elastic WIMP–nucleon cross section. The XENON collaboration also recalculated the limit from CDMS assuming an escape velocity of 544 km/s which fits perfectly inside the  $2\sigma$  limits they obtained, as the less conservative scenario on  $\mathcal{L}_{eff}$ . We also explored the possibility of a projected 1 ton XENON experiment [46] (more or less equivalent to a super CDMS extension of CDMS [47]). During the writing of the article, the XENON experiment published a more detailed analysis for light DM exclusion limit with XENON10 data in [48] and with XENON100 data [49]. Their results are compatible with the exclusion limit we used through the analysis.

### D. Indirect detection

From the indirect detection data, we combined the very last analysis of different experimental groups.

- Observation of Milky Way dwarf spheroidal galaxies by FERMI : dwarf spheroidal galaxies (dSphs), the largest galactic substructures predicted by the CDM scenario, are ideal laboratories for indirect searches for dark matter for several reasons: the mass-to-light ratios in dSphs can be of order 100-1000 showing that they are largely dark matter dominated systems. In addition, dSphs are expected to be relatively free from  $\gamma$ -ray emission from other astrophysical sources as they have no detected neutral or ionized gas, and little or no recent star formation activity which make them very interesting objects for indirect dark matter searches, especially with the FERMI telescope. For our purpose, we will use the two last analysis of the FERMI collaboration: firstly, the study from the observations of 14 dwarf spheroidal galaxies published in

[50], where we will use the data from DRACO observation as the representative milky way satellite, with an assumed Navarro-Frenk-White (NFW [51]) dark matter density profile; secondly, as it has been shown in [52], it is possible to increase the efficiency of the constraints using a combined analysis. Even if preliminary, these results are quite robust<sup>5</sup>. It is useful to stress that for any indirect detection searches, experimental analysis are obtained for a given final state. As we wanted to be the more conservative, we considered their analysis with a  $b\bar{b}$  final state. Indeed, this spectrum is representative of quark spectrum which is the dominant one (due to the color factor) in the decay of a  $Z_D$  in  $s$  or  $t$  channel. Moreover, the final states fraction containing  $\mu^+\mu^-$  or  $\tau^+\tau^-$  (never more than 5 percents in all our points respecting WMAP constraint) produces a hard  $\gamma$ -ray spectrum resulting in much more stringent constraints since they predict abundant photons fluxes at larger energies, where the diffuse background is lower (see [53, 54] for an analysis of these specific channels). For a quark final state, the resulting rays stem dominantly from the decay of neutral pions produced in the quark and anti-quark hadronization chains, and do not crucially depend upon the specific quark flavor or mass; in fact, a very similar ray spectrum is produced by the (typically loop-suppressed) gluon-gluon final state. We thus stay conservative in our analysis. One can also read [55] for a clear review of the status and perspectives of the FERMI satellite.

- Searches from the Galactic Center with HESS: we also included in our analysis the very last searches for a very high  $\gamma$ -ray signal from DM annihilation in our galaxy in the region of 45 pc-150 pc after 112h of observations, excluding the Galactic plane done by the HESS collaboration [56]. These limits are among the best reported so far in this energy range. In this region of the halo, the dependance on the DM profile is quite low, and the *reflected background* technique allows for an intelligent subtraction of the background. The limits can shift by 30% due to both the uncertainty on the absolute flux measurement and the uncertainty of 15% on the energy scale, which does not affect our general conclusion. Note that to be consistent with the FERMI analysis, we adopted the NFW profile parameterization of the HESS results.
- Radio constraints : charged particles production in a halo is necessarily accompanied by radio waves. These signals are produced via the various energy loss processes that charged particles undergo, examples of which include synchrotron radiation or

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<sup>5</sup> Private communication with the author of [52]



inverse Compton scattering of electrons from interstellar radiation field [57–60]. We applied the combined constraints derived using all energy loss processes, featuring only mild dependence on the astrophysical parameters. Radio data provide more severe restrictions for strong magnetic field  $B$ . Taking into account the very large uncertainty on the value of the field in the Galactic center, we studied the constraints for  $B = 30\mu\text{G}$  and  $100\mu\text{G}$ , with the NFW profile to stay consistent with the HESS and FERMI searches. We followed the recent analysis given in [57].

- We also implemented the constraints derived from FERMI diffuse measurements [61]. However, these constraints were always lying between the constraints coming from the DRACO satellite and the ones from the combined dSphs analysis. We thus decided not to show them in the plots.

## IV. RESULTS

### A. Where does hit each experiment?

We show in Fig.1 the electroweak, cosmological and astrophysical constraints in the plane  $(M_{Z_D}; \delta)$  for different DM masses (5, 25, 200 and 500 GeV). One can distinguish 4 regimes : very light DM ( $\sim 5$  GeV) light DM ( $\sim 30$  GeV), heavy ( $\sim 100$  GeV) and very heavy ( $\gtrsim 500$  GeV) DM. Depending on the regime, some constraints will dominate over other ones, making complementarity between all these detections mode fundamental for a general analysis of any  $U'(1)$  extension of the SM. Another interesting region is the parameter space with maximal mixing, where  $M_{Z_D} \sim M_Z$ . However, this region when respecting WMAP constraints is totally excluded because of a large excess of the  $\rho$  parameter.

### B. The (very)light Dark Matter regime

In the case of very light dark matter ( $\lesssim 10$  GeV), the XENON experiment is relatively inefficient. As one can check in Fig.1 (top) all the points respecting WMAP respect also the last data from XENON100. However, some other experiments like FERMI and especially radio constraints become more efficient as was already stressed by the authors of [58] where they showed that a DM mass between 1 and 10 GeV could be excluded by radio data from galactic center. One also notices that the electroweak constraints become the more effective constraints for masses of  $Z_D$ ,  $M_{Z_D} \gtrsim 55$  GeV where they exclude the region respecting WMAP. Indeed, these constraints are obviously independent of the DM mass, but are stringent when the  $Z - Z_D$  mixing is important ( $M_{Z_D} \sim M_Z$ ).

For  $25\text{GeV} \lesssim m_{\psi_0} \lesssim 200$  GeV, one can see that the radio constraints become less effective, whereas the XENON experiment excludes a large part of the parameter space allowed by WMAP except near the pole. Indeed in the region  $(M_{Z_D}; \delta)$  where  $2m_{\psi_0} \simeq M_{Z_D}$ , the  $s$ -channel  $Z_D$  exchange cross section increases dramatically. Points respecting WMAP lie in region of parameter space with low values of  $\delta$  (the "sea-gull" shape in Figs.1) : with such low values of  $\delta$ , the direct detection (through  $t$ -channel  $Z_D$  exchange) cross section  $\sigma_{p\psi_0}$  stays below the XENON100 exclusion limit. However, this  $Z_D$ -pole region is sensitive to indirect detection experiment like FERMI or HESS because of the high value of the annihilating rate  $\psi_0\psi_0 \rightarrow Z_D \rightarrow \bar{f}f$ .

### C. The (very)heavy Dark Matter regime

In this regime, a XENON-like experiment becomes less effective (because of the mass suppression in the scattering cross section) whereas FERMI and HESS indirect detection data exclude the large part of the parameter space around the pole. However, one can check in Fig.1(bottom) that a 500 GeV DM is not yet excluded, except in the region where  $M_{Z_D} \lesssim m_{\psi_0}$ , dominated by the  $\psi_0\psi_0 \rightarrow Z_D Z_D$  annihilation final state. HESS limits become more efficient than FERMI for  $m_{\psi_0} \gtrsim 300$  GeV. Contrary to the (very)light case, the electroweak observables are always less constraining than any astrophysical data given by direct or indirect detection. Whatever is the DM mass, one can check in Figs.1(all) that a XENON 1 ton experiment would be able to exclude all the region respecting WMAP except in a very narrow region around the pole if  $m_{\psi_0} \gtrsim 500$  GeV.

We also analyzed the allowed region in the  $(M_{Z_D}; \delta)$  parameter space after a complete scan on the DM mass  $1\text{GeV} < m_{\psi_0} < 1$  TeV, taking into account the different natures of experimental exclusions. The results are presented in Figs.2. With such a scan, our results become independent of the nature, coupling or mass of the dark matter candidate, and one can compare directly the sensitivity of each type of experiment for specific regions of the parameter space.

It appears clearly that FERMI experiment excludes a region of the parameter space corresponding to  $M_{Z_D} \lesssim 100$  GeV which is the region where the satellite is the more effective. The radio constraints exclude a part of the parameter with lighter  $Z_D$  as expected [57, 58]. The  $\rho$  and EWPT constraints reach the region of the parameter space where  $M_{Z_D} \simeq M_Z$  (maximal mixing). Even after taking into account the XENON100 exclusion region at  $\pm 2\sigma$ , a region respecting WMAP survives around  $M_{Z_D} \simeq 10$  GeV where one can fit COGENT, CRESST or DAMA excesses [18, 22]. One also observes that a 1 ton XENON-like experiment would exclude 99 % of the parameter space allowed by WMAP. It would be quite difficult to escape such constraints as the couplings of

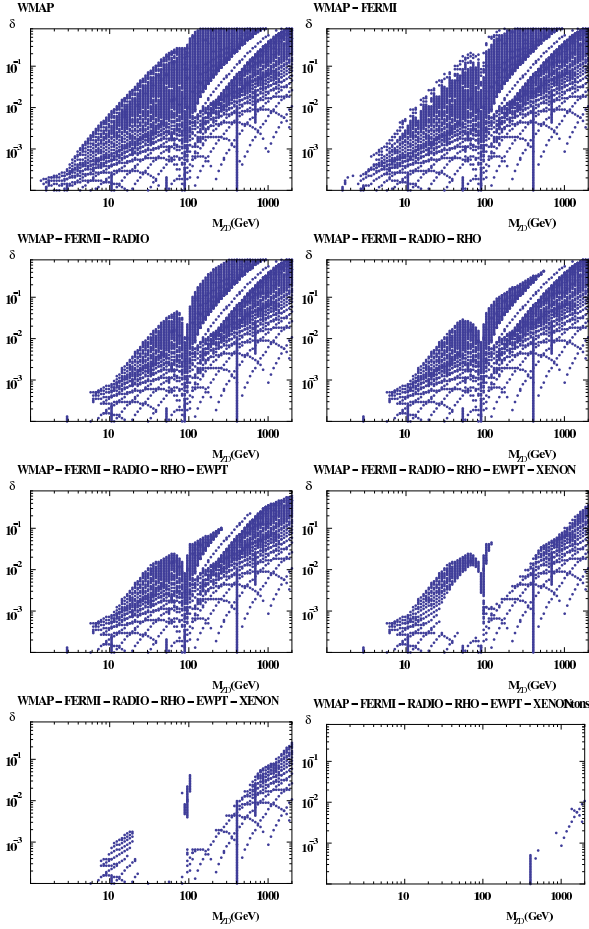


FIG. 2. Parameter space allowed taking account different type of experiments in the  $(m_{\psi_0}; M_{Z_D})$  plane. The two plots taking into account the XENON constraints correspond to the  $+2\sigma$  and  $-2\sigma$  zones of exclusion.

the  $Z_D$  to the quarks are fixed for a given value of  $\delta$ .

We would like to say few words on the "hole" one observes in the parameter space -before taking into account the XENON100 constraints- in Figs.2(top). For a given  $M_{Z_D}$ , when  $\delta$  increases, the  $Z_D$  pole "disappears" in the sense that the relic abundance stays below WMAP data between the  $Z$  and  $Z_D$ -pole: points that respect WMAP constraints lie *very* near from the  $Z$ -pole, especially because for such large values of  $\delta$ , the  $Z$ -pole branch is extremely narrow. Indeed,  $Z\psi_0\psi_0$  coupling is proportional to  $\sin\phi$ , Eq.(4), which means that the annihilation cross section  $\langle\sigma v\rangle \propto \delta^2/\Gamma_Z^2$  ( $\Gamma_Z$  being the width of the  $Z$  boson) is very sensitive. When  $\delta$  increases from  $10^{-3}$  to  $10^{-1}$ , the cross section gains 4 orders of magnitude! One needs an extremely fine tuning (at the 0.1% level) on the condition  $m_{\psi_0} = M_Z/2$  to respect WMAP bounds. This extreme fine-tuning condition respects a law  $\sin\phi = \text{cste} \Rightarrow \delta \propto M_{Z_D}$  (for  $M_{Z_D} \gtrsim M_Z$ , Eq.(4)) which is exactly the shape of the hole of Fig.2(top). For much higher values of  $\delta$ , points do not need to be on the  $Z$ -pole anymore

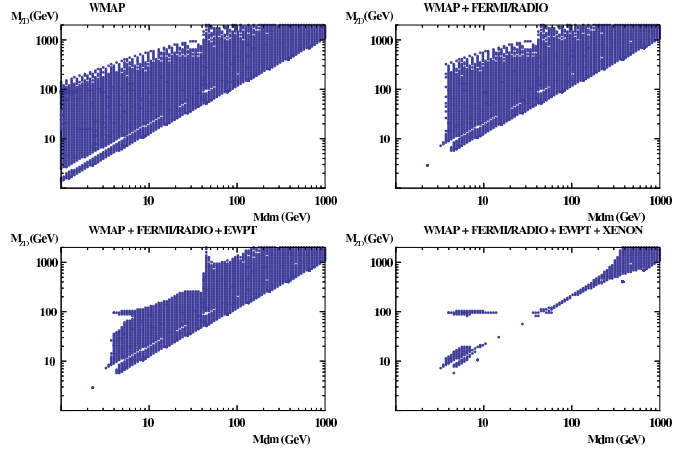


FIG. 3. Parameter space allowed within 90 % of C.L. for the CoGeNT signal (blue), DAMA without channeling (red), with channeling (green), CRESST (black), and the exclusion region depending on the hypothesis concerning  $L_{eff}$  (see the text for details).

to respect WMAP (for  $\delta = 0.8$  and  $M_{Z_D} = 300$  GeV, one enters in WMAP bounds for  $m_{\psi_0} \simeq 3$  GeV). In any case, this region of extreme fine-tuning is largely excluded by XENON100 experiment, even in the more conservative case.

#### D. Consequences on $m_{\psi_0}$ and $M_{Z_D}$

One interesting analysis was to look at the consequences on  $m_{\psi_0}$  independently of  $\delta$ . We show in Figs.3 the region of the parameter space allowed by the different type of experiments in the  $(m_{\psi_0}; M_{Z_D})$  plane after a scan on  $10^{-4} < \delta < 0.8$ . One observes that WMAP restricts the parameter space to a relatively broad region around the line  $M_{Z_D} \sim 2m_{\psi_0}$ . After taking into account the indirect detection constraints, the region of light mass is excluded as expected. The EWPT and  $\rho$ -parameter exclude the region near  $M_{Z_D} \sim M_Z$  (maximal mixing) and further from the pole because the further one stays from the pole region, the higher the value of  $\delta$  should be to respect WMAP<sup>6</sup>, at the risk to be excluded by EWPT. Once we consider the exclusion limit by XENON100, the only points surviving are the ones lying exactly on the pole line  $M_{Z_D} = 2m_{\psi_0}$ : in this region, one needs on the contrary a very small value of  $\delta$  ( $\sim 10^{-3}$ ) to respect WMAP because of the high annihilation cross section of the process  $\psi_0\psi_0 \rightarrow Z_D \rightarrow \bar{f}f$ . Such small values for  $\delta$  respect XENON100 exclusion limits. One also notices a vertical breaking step in the parameter space for

<sup>6</sup> We also notice that even more stringent constraints from WMAP could have been applied [62], but we wanted to stay as conservative as possible in our study.

$m_{\psi_0} \simeq 45$  GeV (before applying the XENON100 constraints) which corresponds to the  $Z$ -pole region. It is interesting to point out that there still exists a bulk region around  $m_{\psi_0} \simeq 7$  GeV not yet excluded by XENON and which is able to explain the last CRESST/CoGENT data [22, 23]. We should mention that this model has a common feature with the singlet extension of the SM studied in [26, 27]: the same diagram which gives the relic abundance is the one contributing to the nucleon-scattering (from  $s$ - to  $t$ - channel  $Z_D$  exchange). One can demonstrate that these sorts of models usually ensure a large direct detection rate.

## V. CONCLUSION AND SUMMARY

We showed that the existence of a *dark*  $U_D(1)$  gauge sector which interacts with the Standard Model only through its kinetic mixing possesses a valid dark matter candidate respecting accelerator, cosmological and the more recent direct detection constraints. We observed that when one combines direct and indirect detection

searches, the restrictions are much more stringent than the ones extracted by precision test measurements. All these experiments are indeed complementary, excluding different parts of the parameter space allowed by WMAP. Moreover, once we take into account all these constraints, only a narrow region of the parameter space along the  $Z_D$ -pole region  $M_{Z_D} = 2m_{\psi_0}$  survives. There is still a bulk region around  $m_{\psi_0} \simeq 7$  GeV which can explain the recent excesses observed in some direct detection experiments. We also showed that a 1ton XENON-like experiment would be able to test more than 90% of the remaining parameter space, being able to exclude (discover?) robustly such models.

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